

Strangeness enhancement at LHC

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Abstract. We study production of strangeness in the hot QGP fireball in conditions achieved at LHC, and use these results to obtain soft (strange) hadron multiplicities. We compare the chemical equilibrium and non-equilibrium conditions and identify characteristic experimental observables.

PACS numbers: 24.10.Pa, 25.75.-q, 13.60.Rj, 12.38.Mh

1. Introduction

We address here the bulk matter hadronization at LHC-ion. This work represents a synthesis of insights we published in past 2 years [1, 2], and it comprises a comparative study of LHC bulk hadronization. One of the points of interest is how, as function of increasing energy of colliding nuclei, the hadronization of the dense quark–gluon matter fireball occurs — experimental evidence suggests that at sufficiently high energy, e.g., at RHIC, this happens in a rapid and explosive manner. The LHC-ion research program should allow exploration of even more extreme conditions.

Since QGP phase is entropy rich, compared to the hadron phase, additional entropy production at hadronization hinders hadronization. Thus, in the explosive QGP breakup process, we expect entropy to be preserved. Moreover, also the flow of QGP matter seems to occur without a significant entropy production [3]. Thus, the entropy (per unit rapidity) dS_0/dy produced in the early reaction state is also nearly the entropy present in the QGP breakup. This means that the total final state hadron multiplicity prior to hadron resonance decay is a measure of initial entropy production, which occurs predominantly during the thermalization stage [4]. We will constrain the initial state conditions by considering the final state entropy (hadron multiplicity) expected at LHC.

Our study of the strange quark production processes is based on kinetic theory of particle collisions, and as is well known, the gluon collisions are driving strangeness to chemical equilibrium in hot QGP. This seems to depend on the degree of chemical equilibration in the early QGP phase. However, the observable final specific ‘strangeness pair yield per entropy’ N_s/S (also colloquially referred to as s/S) ratio is found to be rather insensitive to this uncertainty. This expresses the fact that, at a given entropy content, the temperature can be high at low particle yield, or vice-versa, temperature can be low, but particle number large. In the cumulative strangeness production process,

these effects compensate, the final strangeness yield is not initial state dependent (i.e., not dependent on full gluon equilibration) [2]. This observation illustrates the fact that strangeness is not a ‘deep’ observable of QGP, that is we cannot use it to study conditions prevailing at the early stage of heavy ion reaction.

After a brief discussion of the kinetic strangeness production which allows us to evaluate the expected strangeness yield, we turn our attention to the properties of the fireball of matter and its breakup (hadronization).

2. Strangeness chemical equilibration in QGP at LHC

Both strangeness and entropy are nearly conserved near, and at hadronization, and thus the final state s/S , is closely related to the thermal processes in the fireball at $\tau \simeq 1\text{--}4$ fm/c. The measurement of s/S involves study of strange and non-strange hadrons and extrapolation of unobserved yields, required to evaluate the entropy locked in hadron multiplicity. In order to evaluate the magnitude of s/S in the QGP phase, we consider the hot early stage of the reaction. For an equilibrated QGP phase with perturbative properties, we have (superscript ‘G’ indicates that this quantity is referring to QGP phase).

$$\frac{s}{S} \equiv \frac{\rho_s}{S/V} \simeq \frac{(\gamma_s^G(t)g_s/\pi^2)T^3 0.5 x^2 K_2(x)}{g 4\pi^2/90 T^3} = \frac{\gamma_s^G g_s}{g} 0.23[0.5 x^2 K_2(x)]. \quad (1)$$

For early times, when $x = m_s/T(t)$ is relatively small, the equilibrium value of strangeness QGP phase space occupancy ($\gamma_s^G = 1$) can be as large as $s/S > 0.04$. However, at high temperature, strangeness is not yet equilibrated chemically. For $m_s/T \simeq 0.7$, appropriate for hadronization stage, the QGP chemical equilibrium is reached when $s/S \simeq 0.04$.

The temporal evolution of s/S , in an expanding plasma, is governed by:

$$\frac{d}{d\tau} \frac{N_s}{S} = \frac{A^{gg \rightarrow s\bar{s}}}{(S/V)} [(\gamma_g^G(\tau))^2 - (\gamma_s^G(\tau))^2] + \frac{A^{q\bar{q} \rightarrow s\bar{s}}}{(S/V)} [(\gamma_q^G(\tau))^2 - (\gamma_s^G(\tau))^2] \quad (2)$$

When all $\gamma_i \rightarrow 1$, the Boltzmann collision term vanishes, and equilibrium has been reached. Here, we use the invariant rate per unit time and volume, $A^{12 \rightarrow 34}$, by incorporating the chemical equilibrium densities into the thermally averaged cross sections:

$$A^{12 \rightarrow 34} \equiv \frac{1}{1 + \delta_{1,2}} \gamma_1 \gamma_2 \rho_1^\infty \rho_2^\infty \langle \sigma_s v_{12} \rangle_T^{12 \rightarrow 34}. \quad (3)$$

$\delta_{1,2} = 1$ for reacting particles being identical bosons, $\delta_{1,2} = 0$ otherwise. γ_i expresses the deviation from equilibrium of density ρ_i . Note also that the evolution for s and \bar{s} , in proper time of the co-moving volume element, is identical as both change in pairs.

We evaluate $A^{gg \rightarrow s\bar{s}}$ and $A^{q\bar{q} \rightarrow s\bar{s}}$ employing the available strength of the QCD coupling, and $m_s(\mu = 2 \text{ GeV}) = 0.10 \text{ GeV}$ for the strange quark mass. We compute rate of reactions employing a running strange quark mass working in two loops, and using as the energy scale the CM-reaction energy $\mu \simeq \sqrt{s}$. For the QCD coupling constant,

we use as reference value $\alpha_s(\mu = m_{Z^0}) = 0.118$, and evolve the value to applicable energy domain μ by using two loops. We introduce a multiplicative factor $K = 1.7$, which accounts for processes odd in power of α_s , such as gluon fusion into strangeness, with gluon bremsstrahlung emitted by one of the strange quarks. Being distinguishable, ‘even’ and ‘odd’ terms are contributing incoherently, always increasing the production rate. The magnitude of K , is estimated based on perturbative QCD Drell–Yan lepton pair production [5], and heavy quark production [6].

In order to evaluate strangeness production, we need to understand $T(\tau)$. Hydrodynamic expansion with Bjorken scaling [4], and small viscosity implies that $dS/dy \equiv \sigma(T)dV/dy = \text{Const.}$ as function of time. This means that $dV/dy(\tau)$ expansion fixes $\sigma(\tau)$, thus based on equations of state, also $T(\tau)$. We parametrize $dV/dy \propto A_\perp dz/dy|_{\tau,y}$ where in Bjorken scaling limit $dz/dy|_{\tau,y} = \tau \cosh y$. Thus, the ad-hoc model element is the transverse flow, which defines the size of the transverse fireball slice, $A_\perp(\tau)$. Our model explorations of ‘reasonable’ forms of $A_\perp(\tau)$ suggest that the controlling factor in the determination of s/S at freeze-out is the final size of the fireball along with final velocity, and not the system history. This is consistent with our earlier observation that strangeness is not a ‘deep’ observable of QGP.

The value of s/S is mainly uncertain due to unknown initial entropy S_0 , and the strange quark mass. The latter uncertainty does not impact the degree of strangeness chemical equilibration in QGP: for smaller mass, more strangeness can be made, but also more strangeness is needed to equilibrate the higher phase space density. These two effects cancel nearly exactly in a wide range of model parameters. Thus, the achievement of $\gamma_s^G \rightarrow 1$ chemical equilibrium in QGP is not a model dependent outcome, and is in essence a result of entropy content provided by heavy ion collisions. However, the actual final specific yield s/S varies according to Eq. (1). In what follows, we assume chemical equilibration in QGP.

3. Soft Hadrons at LHC

The phase space density is, in general, different in any two phases. Hence, when transformation of one phase into the other occurs rapidly, given chemical equilibrium in the decaying phase, the final state is out-of chemical equilibrium. Thus, in order to preserve entropy, there must be a jump in the phase space occupancy parameters $\gamma_i^G < \gamma_i$ (When we omit superscript on γ this quantity refers to hadron phase space.) This jump replaces the increase in volume found in a slow transformation involving yield re-equilibration, which is required in a putative chemical equilibrium approach. In order to preserve entropy in sudden hadronization of supercooled QGP at $T \simeq 140$ MeV, we must have $\gamma_q^{\text{cr}} = e^{m_\pi/T}$. The value γ_q^{cr} is where the pion gas condenses. The required value of γ_q is decreasing with increasing temperature and crossing $\gamma_q = 1$ near $T \simeq 180$ MeV. We study the soft hadron production at LHC subject to the following constraints and inputs, using the statistical hadronization model (SHM) implemented in the package SHARE 2 [7]:

- (i) The extrapolation as function of $\ln \sqrt{s_{\text{NN}}}$ implies an increase of dS/dy by a factor 1.65 at LHC-5520 compared to RHIC-200 (numerals refer to $\sqrt{s_{\text{NN}}}$). However, we also consider the case of 3.4-fold increase in particle multiplicity, that is within a TPC the charged track number is $h = 2924$. This yield occurs in hadron gas in chemical equilibrium at the final volume $dV/dy = 6200 \text{ fm}^3$.
- (ii) We take strangeness content from pQCD considerations discussed above, which at LHC implies QGP near chemical equilibrium conditions. This can be compared to expectations assuming hadron equilibrium condition.
- (iii) We fix the value of μ_B and by strangeness balance $\langle s \rangle = \langle \bar{s} \rangle$ also of μ_S . We do this aiming to obtain for the specific energy per net baryon $E/(b - \bar{b}) \simeq 415 \pm 20 \text{ GeV}$, a value to which our study of SPS and RHIC extrapolates to. We make sure that the resulting charge per net baryon ratio $Q/(b - \bar{b}) = 0.4$ is as provided by the proton to neutron ratio in heavy ions.
- (iv) We fix as hadronization condition for sudden break up model $\gamma_q = 1.6$ and $T_f = 140 \text{ MeV}$; the value of γ_s follows from specific strangeness conservation s/S in hadronization. For the simple hadron model, we take $T_f = 162 \text{ MeV}$ and $\gamma_q = \gamma_s = 1$.
- (v) We bias our fit towards $\pi^+/\pi^- \simeq 1$. For the non-equilibrium hadronization, we also bias $E/TS \simeq 1$. This constrains the search of the minimum considerably and renders the result more numerically stable.

In table 1, we present in the column on left the properties of the fireball consistent with hadron yields extrapolated using PHOBOS-RHIC charged particles yield, which at LHC yields $dh_{\text{charged}}/dy = 1150$ [8]. In the second column, we fix the visible hadron multiplicity in STAR like set-up, to correspond to a reference value obtained in the chemical equilibrium model, with volume fixed [9] in order to increase the hadron yield by about factor 3.4. This results in enhanced entropy content, dS/dy and thus, we use somewhat higher specific strangeness content s/S , in accordance with our kinetic strangeness production computation.

The high specific strangeness yield of the chemical non-equilibrium model is expressed by the large value $\gamma_s > 1$. The low temperature at freeze-out ($T_f = 140 < 161 \text{ MeV}$) leads to $\gamma_q \simeq 1.6$. While this value is result of a constraint to stop condensation of pions, one can show that this value preserves entropy contents of QGP in the HG phase [10]. Despite the lower value of T_f in the non-equilibrium model, the fireball has greater energy and entropy density. As the entries in table 1 show, this is in essence due to a significantly greater strange hadron contents. Generally, there are several distinctive hadron multiplicity features of hadronization models. In particular, enhanced production of multistrange hadrons occurring at the same time as somewhat suppressed resonance production, is a strong indication that rapid, non-equilibrium breakup of QGP is present.

4. Discussion

One is tempted to wonder if and why the use of chemical non-equilibrium parameters matters. Note that the yield of baryons is proportional to $V\gamma_q^3(\gamma_s/\gamma_q)^{n_s}$, where n_s is the total number of constituent strange quarks or anti-quarks. Similarly, the yield of mesons is proportional to $V\gamma_q^2(\gamma_s/\gamma_q)^{n_s}$. Thus, ratio of baryons to mesons at fixed value of γ_s/γ_q is dependent on the value of γ_q . The parameter γ_q allows us to increase the yield of baryons compared to the yield of mesons. This is a very important feature considering that microscopic pictures of quark recombination.

Given the mass difference between mesons and baryons, T_f also impacts the relative meson to baryon ratio. However, solely T_f influences the relative resonance yield, and should for this reason not be ad-hoc manipulated to balance the baryon to meson yield. A consequence of fixing (arbitrarily) $\gamma_q = 1$ is that the overall ratio of baryons to mesons fixes the value of T_f and predicts resonance yields which, in general, at RHIC disagree with experiment by up to 50%. This (in part) explains why, when $\gamma_q \neq 1$, one finds fits of experimental data which are a lot better than for $\gamma_q = 1$. We note that there have been efforts to explain the reduced yields by rescattering of daughter particles. Our sudden hadronization approach is simpler and the outcome has no fine-tuned reaction parameters. It is possible using double resonance ratios to differentiate these models. As a third point, ad-hock assumption of a value expected in a perfect world, viz. chemical hadron equilibrium $\gamma_q = 1$ presumes also that the SHM model is completely understood. In our opinion γ_q a) helps to compensate model omissions (e.g., hadron widths not considered in general, though available in SHARE), and, b) corrects for evolving but at present still incomplete knowledge of hadron spectra. We conclude that introduction of γ_q , within the SHM, is a necessary model feature.

Another LHC soft hadron abundance controlling parameter is γ_s/γ_q , which influences all strange to non-strange particle yields, allows to preserve strangeness yield across the phase boundary. At LHC, we expect greater intrinsic strangeness content, and thus, a relatively large value of γ_s/γ_q , which enters with power n_s for the number of valance strange quark we compare non-strange hadrons with. Since strange hadrons are in general more massive than non-strange, the higher equilibrium model $T_f \simeq 161$ MeV in part compensates the model strangeness suppression for singly strange hadrons, but multistrange hadrons allow to discriminate models, and thus, to understand the properties of QGP at hadronization, and hadronization dynamics.

Acknowledgments Work supported by a grant from: the U.S. Department of Energy DE-FG02-04ER4131. LPTHE, Univ.Paris 6 et 7 is: Unité mixte de Recherche du CNRS, UMR7589

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Table 1. Fireball properties at freeze-out, followed by particle yields (prior/after weak decays) and ratios. First two columns, the chemical non-equilibrium model, equilibrium model follows in the last column. See text for details. Star ‘*’ indicates a fixed value, i.e. input used to characterize the model. We bold-face 40%+difference of chemical non-equilibrium to equilibrium models.

$T[\text{MeV}]$	140*	140*	161*
$dV/dy[\text{fm}^3]$	2126	4223	6200*
dS/dy	7457	16278	18790
$b - \bar{b}$	2.6	5.5	6.4
dh_{ch}/dy (PHOBOS)	1150*	2435	2538
$dh_{\text{ch}}^{\text{vis}}/dy$ (STAR)	1350	2924* \rightarrow	2924
$(b + \bar{b})/h^-$	0.334	0.353	0.370
$1000 \cdot (\lambda_{q,s} - 1)$	5.6*, 2.1*	5.6*, 2.1*	5.6*, 2.0*
$\mu_{B,S}[\text{MeV}]$	2.3*, 0.5*	2.3*, 0.5*	2.7*, 0.6*
$\gamma_{q,s}$	1.6*, 2.35	1.6*, 2.8	1*, 1*
s/S	0.034*	0.038*	0.0255
$E/(b - \bar{b})$	423	431	404
E/TS	1.04	1.04	0.86
P/E	0.165	0.162	0.162
$E/V[\text{MeV}/\text{fm}^3]$	509	560	420
$S/V[1/\text{fm}^3]$	3.51	3.86	3.03
$(s + \bar{s})/V[1/\text{fm}^3]$	0.119	0.147	0.077
$0.1 \cdot \pi^\pm$	49/61	102/132	115/132
p	25/45	50/101	71/111
Λ	19/27	45/70	40/53
K^\pm	94	226	183
ϕ	14	38	25
Ξ^-	3.9	11	6.2
Ω^-	0.78	2.6	0.98
Δ^0, Δ^{++}	4.7	9.4	14.6
$K_0^*(892)$	22	52	55
η	62	149	133
η'	5.2	13.2	12.1
ρ	36	74	119
ω	32	65	109
f_0	2.8	5.6	10.2
K^+/π_{vis}^+	0.164	0.184	0.148
$\Xi^-/\Lambda_{\text{vis}}$	0.143	0.159	0.116
$\Lambda(1520)/\Lambda_{\text{vis}}$	0.044	0.041	0.060
$\Xi(1530)^0/\Xi^-$	0.33	0.33	0.36
$1000\phi/h_{\text{ch}}^{\text{vis}}$	10	13	8.4
$K_0^*(892)/K^-$	0.237	0.232	0.303